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▶ **To cite this version:**

H.O. Back, M. Balata, A. de Bari, T. Beau, A. de Bellefon, et al.. New limits on nucleon decays into invisible channels with the BOREXINO counting test facility. Physics Letters B, 2003, 563, pp.23-34. in2p3-00013809

HAL Id: in2p3-00013809
https://hal.in2p3.fr/in2p3-00013809

Submitted on 8 Jul 2003

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arXiv:hep-ex/0302002 v2 25 Mar 2003

New limits on nucleon decays into invisible channels with the BOREXINO Counting Test Facility

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Abstract

The results of background measurements with the second version of the BOREXINO Counting Test Facility (CTF-II), installed in the Gran Sasso Underground Laboratory, were used to obtain limits on the instability of nucleons, bounded in nuclei, for decays into invisible channels (*inv*): disappearance, decays to neutrinos, etc. The approach consisted of a search for decays of unstable nuclides resulting from N and NN decays of parent ^{12}C, ^{13}C and ^{16}O nuclei in the liquid scintillator and the water shield of the CTF. Due to the extremely low background and the large mass (4.2 ton) of the CTF detector, the most stringent (or competitive) up-to-date experimental bounds have been established: $\tau(n \to inv) > 1.8 \cdot 10^{25}$ y, $\tau(p \to inv) > 1.1 \cdot 10^{26}$ y, $\tau(nn \to inv) > 4.9 \cdot 10^{25}$ y and $\tau(pp \to inv) > 5.0 \cdot 10^{25}$

y, all at 90% C.L.

Key words: proton decay, baryon number conservation, scintillation detector
PACS: 11.30, 11.30.F, 12.60, 29.40.M

1 Introduction

The baryon (B) and lepton (L) numbers are considered to be conserved in the Standard Model (SM) [6] . However, no symmetry principle underlies these laws, such as, e.g. gauge invariance, which guarantees conservation of the electric charge. Many extensions of the SM include B and L violating interactions, predicting the decay of protons and neutrons bounded in nuclei. Various decay mechanisms with ΔB=1, 2 and $\Delta(B–L)$=0, 2 have been discussed in the literature intensively [2,3]. A novel baryon number violating process, in which two neutrons in a nucleus disappear, emitting a bulk majoron $nn \rightarrow \chi$, was proposed recently [4]; the expected mean lifetime was estimated to be $\sim 10^{32-39}$ y. Additional possibilities for the nucleon (N) decays are related to theories which describe our world as a brane inside higher-dimensional space [5,6]. Particles, initially confined to the brane, may escape to extra dimensions, thus disappearing for the normal observer; the characteristic proton mean lifetime was calculated to be $\tau(p)=9.2\cdot 10^{34}$ y [7]. Observation of the disappearance of

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†Project manager
□Operational manager
△GLIMOS
•Task manager
[6] It should be noted that nonperturbative effects at high energies can lead to the B and L violation even in the SM [1].

e^-, N, NN would be a manifestation of the existence of such extra dimensions [6].

No evidence for nucleon instability has been found to date. Experimental searches [8] with the IMB, Fréjus, (Super)Kamiokande and other detectors have been devoted mainly to nucleon decays into strongly or electromagnetically interacting particles, where lower limits on the nucleon mean lifetime of 10^{30-33} y were obtained [9]. At the same time, for modes where N or NN pairs disappear or they decay to some weakly interacting particles (neutrinos, majorons, etc.), the experimental bounds are a few orders of magnitude lower. Different methods were applied to set limits for such decays [7] (see table 1 for summary):

(1) Using the limit on the branching ratio of spontaneous fission of ^{232}Th under the assumption that p or n decay in ^{232}Th will destroy the nucleus [10]. The bound on the mean lifetime obtained in this way can be considered independent of the a p or n decay mode, since the ^{232}Th nucleus can be destroyed either by strong or electromagnetic interactions of daughter particles with the nucleus or, in the case of N disappearance, by subsequent nuclear deexcitation process;

(2) Search for a free n created after p decay or disappearance in the deuterium nucleus (d=pn) in a liquid scintillator enriched in deuterium [11] or in a volume of D_2O [12,16,17];

(3) Geochemical [13] or radiochemical [14] search for daughter nuclides which have appeared after N decays in the mother nuclei (valid for decays into invisible channels);

(4) Search for prompt γ quanta emitted by a nucleus in a de-excitation process after N decays within the inner nuclear shell [18] (valid for invisible channels);

(5) Considering the Earth as a target with nucleons which decay by emitting electron or muon neutrinos; the ν_e, ν_μ can be detected by a large underground detector [19,20] (valid for decay into neutrinos with specific flavors);

(6) Search for bremsstrahlung γ quanta emitted due to a sudden disappearance of the neutron magnetic moment [21] (limits depend on the number of emitted neutrinos);

(7) Study of radioactive decay of daughters (time-resolved from prompt prod-

[7] We are using the following classification of decay channels: decay to invisible channel (*inv*) means disappearance or decay to weakly interacting particles (one or few neutrinos of any flavors, majorons, etc.). Channel to *anything*, mentioned below, includes also decays to *inv*.

Table 1
Lower limits on the mean lifetime for decay of nucleons, bounded in nuclei, into invisible channels established in various approaches (see footnote 7 for channels classification).

N or NN decay		τ limit, y and C.L.	Year, reference and short explanation
p	$\to$ *anything*	$1.2{\cdot}10^{23}$	1958 [10] limit on ^{232}Th spontaneous fission
		$3.0{\cdot}10^{23}$	1970 [11] search for free n in liquid scintillator enriched in deuterium ($d \to n+?$)
		$4.0{\cdot}10^{23}$ 95%	2001 [12] free n in D_2O volume
	$\to$ *inv*	$7.4{\cdot}10^{24}$	1977 [13] geochem. search for ^{130}Te$\to$...$\to^{129}$Xe
		$1.1{\cdot}10^{26}$	1978 [14] radiochem. search for ^{39}K$\to$...$\to^{37}$Ar
		$1.9{\cdot}10^{24}$ 90%	2000 [15] search for ^{128}I decay in ^{129}Xe detector
		$\sim 10^{28}$	2002 [16] free n in D_2O volume
		$3.5{\cdot}10^{28}$ 90%	2003 [17] free n in D_2O volume
		$1.1{\cdot}10^{26}$ 90%	2003 [[a]] search for ^{12}B decay in the CTF detector
n	$\to$ *anything*	$1.8{\cdot}10^{23}$	1958 [10] limit on ^{232}Th spontaneous fission
	$\to$ *inv*	$8.6{\cdot}10^{24}$	1977 [13] geochem. search for ^{130}Te$\to$...$\to^{129}$Xe
		$1.1{\cdot}10^{26}$	1978 [14] radiochem. search for ^{39}K$\to$...$\to^{37}$Ar
		$4.9{\cdot}10^{26}$ 90%	1993 [18] search for γ with E_γ=19–50 MeV emitted in ^{15}O deexcitation in Kamiokande detector
		$1.8{\cdot}10^{25}$ 90%	2003 [[a]] search for ^{11}C decay in the CTF
	$\to \nu_\mu\overline{\nu}_\mu\nu_\mu$	$5.0{\cdot}10^{26}$ 90%	1979 [19] massive liquid scint. detector fired by ν_μ in result of n decays in the whole Earth [b,c]
		$1.2{\cdot}10^{26}$ 90%	1991 [20] Fréjus iron detector fired by ν_μ [c]
	$\to \nu_e\overline{\nu}_e\nu_e$	$3.0{\cdot}10^{25}$ 90%	1991 [20] Fréjus iron detector fired by ν_e [d]
	$\to \nu_i\overline{\nu}_i\nu_i$	$2.3{\cdot}10^{27}$ 90%	1997 [21] search for bremsstr. γ with E_γ>100 MeV emitted due to sudden disapp. of n magn. moment (from Kamiokande data) [e]
	$\to \nu_i\overline{\nu}_i\nu_i\overline{\nu}_i\nu_i$	$1.7{\cdot}10^{27}$ 90%	1997 [21] the same approach [e]
nn	$\to \nu_\mu\overline{\nu}_\mu$	$6.0{\cdot}10^{24}$ 90%	1991 [20] Fréjus iron detector fired by ν_μ [f]
	$\to \nu_e\overline{\nu}_e$	$1.2{\cdot}10^{25}$ 90%	1991 [20] Fréjus iron detector fired by ν_e [g]
	$\to$ *inv*	$1.2{\cdot}10^{25}$ 90%	2000 [15] search for ^{127}Xe decay in ^{129}Xe detector
		$4.2{\cdot}10^{25}$ 90%	2002 [22] radiochem. search for ^{39}K$\to$...$\to^{37}$Ar [h]
		$4.9{\cdot}10^{25}$ 90%	2003 [[a]] search for ^{10}C and ^{14}O decay in the CTF
pp	$\to$ *inv*	$5.5{\cdot}10^{23}$ 90%	2000 [15] search for ^{127}Te decay in ^{129}Xe detector
		$5.0{\cdot}10^{25}$ 90%	2003 [[a]] search for ^{11}Be decay in the CTF detector
pn	$\to$ *inv*	$2.1{\cdot}10^{25}$ 90%	2002 [22] radiochem. search for ^{39}K$\to$...$\to^{37}$Ar [h]

[a] This work
[b] The result of [19] was reestimated in [20] to be more than one order of magnitude lower
[c] The limit is also valid for $p \to \nu_\mu\overline{\nu}_\mu\nu_\mu$ decay
[d] The limit is also valid for $p \to \nu_e\overline{\nu}_e\nu_e$ decay
[e] $i = e, \mu, \tau$
[f] The limit is also valid for pn and pp decays into $\nu_\mu\overline{\nu}_\mu$
[g] The limit is also valid for pn and pp decays into $\nu_e\overline{\nu}_e$
[h] On the base of the data of ref. [14]

ucts), created as a result of N or NN decays of the mother nuclei, incorporated into a low-background detector (valid for decay into invisible channels). This method was first exploited by the DAMA group with a liquid Xe detector [15].

In the present paper we use the same approach to search for N and NN instability with the Counting Test Facility, a 4.2 ton prototype of the multiton BOREXINO detector for low energy solar neutrino spectroscopy [23]. The preliminary results were presented in [24].

2 Experimental set-up and measurements

2.1 Technical information about CTF and BOREXINO

BOREXINO, a real-time 300 ton detector for low-energy neutrino spectroscopy, is nearing completion in the Gran Sasso Underground Laboratory (see [23] and refs. therein). The main goal of the detector is the measurement of the ^{7}Be solar neutrino flux via $\nu - e$ scattering in an ultra-pure liquid scintillator, while several other basic questions in astro- and particle physics will also be addressed.

The Counting Test Facility (CTF), installed in the Gran Sasso Underground Laboratory, is a prototype of the BOREXINO detector. Detailed reports on the CTF results have been published [23,25,26], and only the main characteristics of the set-up are outlined here.

The CTF consists of an external cylindrical water tank ($\oslash$11$\times$10 m; $\approx$1000 t of water) serving as passive shielding for 4.2 m^3 of liquid scintillator (LS) contained in an inner spherical vessel of $\oslash$2.0 m. High purity water with a radio-purity of $\approx 10^{-14}$ g/g (U, Th), $\approx 10^{-12}$ g/g (K) and <2 μBq/l for ^{222}Rn is used for the shielding. The LS was purified to the level of $\simeq 10^{-16}$ g/g in U/Th contamination.

We analyze here the data following the upgrade of the CTF (CTF-II). The liquid scintillator used at this stage was a phenylxylylethane (PXE, $C_{16}H_{18}$) with p-diphenylbenzene (para-terphenyl) as a primary wavelength shifter at a concentration of 2 g/l along with a secondary wavelength shifter 1,4-bis-(2-methylstyrol)-benzene (bis-MSB) at 50 mg/l. The density of the scintillator is 0.996 kg/l. The scintillator principal de-excitation time is less than 5 ns which provides a good position reconstruction. In the CTF-II an additional nylon screen between the scintillator vessel and PMTs (against radon penetration) and a muon veto system were installed.

The scintillation light is collected with 100 phototubes (PMT) fixed to a 7 m diameter support structure inside the water tank. The PMTs are fitted with light concentrators which provide a total of 21% optical coverage. The number of photoelectrons measured experimentally is 3.54 per PMT for 1 MeV electrons at the detector's center.

For each event the charge and timing of hit PMTs are recorded. Each channel is supported by an auxiliary channel, the so-called second group of electronics, used to record all events coming within a time window of 8.2 ms after the trigger, which allows tagging of fast time-correlated events with a decrease of the overall dead time of the detector. For longer delays, the computer clock is used providing the accuracy of ≈0.1 s. Event parameters measured in the CTF include the total charge collected by the PMTs during 0–500 ns, used to determine an event's energy; the charge in the "tail" of the pulse (48–548 ns) which is used for pulse shape discrimination; PMT timing, used to reconstruct the event's position; and the time elapsed between sequential events, used to tag time-correlated events.

2.2 Detector calibration

The energy of an event in the CTF detector is defined using the total collected charge from all PMT's. In a simple approach the energy is supposed to be linear with respect to the total collected charge. The coefficient linking the event energy and the total collected charge is called light yield (or photoelectron yield). The light yield for electrons can be considered linear with respect to its energy only for energies above 1 MeV. At low energies the phenomenon of "ionization quenching" violates the linear dependence of the light yield versus energy [27]. The deviations from the linear law can be taken into account by the ionization deficit function $f(k_B, E)$, where k_B is an empirical Birks' constant. For the calculations of the ionitazion quenching effect for PXE scintillator we used the KB program from the CPC library [28]. The "ionization quenching" effect leads to a shift in the position of the full energy peak for gammas on the energy scale calibrated using electrons. In fact, the position of the 1461 keV ^{40}K gamma in the CTF-II data corresponds to 1360 keV of energy deposited for an electron.

The detector energy and spatial resolution were studied with radioactive sources placed at different positions inside the active volume of the CTF. A typical spatial 1σ resolution is 10 cm at 1 MeV. The studies showed also that the total charge response of the CTF detector can be approximated by a Gaussian. For energies $E \geq 1$ MeV (which are of interest here), the relative resolution can be expressed as $\sigma_E/E = \sqrt{3.8 \cdot 10^{-3}/E + 2.3 \cdot 10^{-3}}$ (E is in MeV) [29] for events uniformly distributed over the detector's volume.

The energy dependence on the collected charge becomes non-linear for the energies $E \simeq 4.5$ MeV in the first group of electronics because of the saturation of the ADCs used. In this region we are using only the fact of observing or not-observing candidate events, hence the mentioned nonlinearity doesn't influence the result of the analysis.

Further details on the energy and spatial resolutions of the detector and ionization quenching for electrons, γ quanta and α particles can be found in [29,30].

2.3 Muon veto

The upgrade of the CTF was equipped with a carefully designed muon veto system. It consists of 2 rings of 8 PMTs each, installed at the bottom of the tank. The radii of the rings are 2.4 and 4.8 m. Muon veto PMTs are looking upward and have no light concentrators. The muon veto system was optimized in order to have a negligible probability of registering the scintillation events in the so-called "neutrino energy window" (250–800 keV). The behaviour of the muon veto at the higher energies has been specially studied for the present work. Experimental measurements with a radioactive source (chain of ^{226}Ra) [31] gave, for the probability $\eta(E)$ of identification of an event with energy E in the LS by the muon veto, the value of (1±0.2)% in the 1.8–2.0 MeV region (see fig. 3 later). The energy dependence of $\eta(E)$ was also calculated by a ray-tracing Monte Carlo method accounting for specific features of the light propagation in the CTF which are detailed in [26]. The calculated function was adjusted to reproduce correctly the experimental measurements with the ^{226}Ra source.

2.4 Data selection

As it will be shown below, the candidate events, relevant for our studies, have to satisfy the following criteria: (1) the event should occur in the active volume of the detector and must not be accompanied by the muon veto tag; (2) it should be single (not followed by a time-correlated event); (3) its pulse shape must correspond to that of events caused by γ or β particles.

The selection and treatment of data (spatial cuts, analysis of an event's pulse shape to distinguish between electrons and α particles, suppression of external background by the muon veto system, etc.) is similar to that in ref. [30].

The experimental energy spectra in CTF-II, accumulated during 29.1 days of measurements, are shown in fig. 1. The spectrum without any cuts (spectrum

1) is presented on the top. The second spectrum is obtained by applying the muon cut, which suppressed the background rate by up to two orders of magnitude, depending on the energy region.

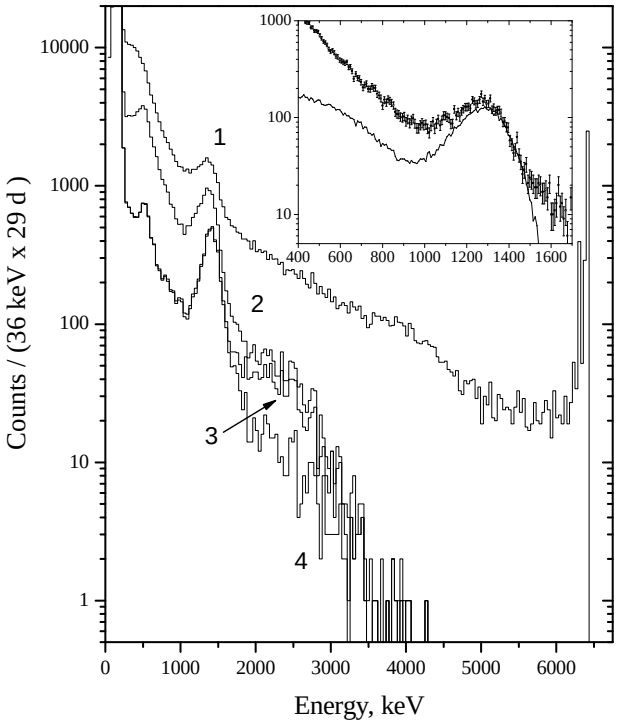


Fig. 1. Background energy spectra of the 4.2 ton BOREXINO CTF-II detector measured during 29.1 days. From top to bottom: (1) spectrum without any cuts; (2) with muon veto; (3) only events inside the radius $R{\leq}100$ cm with additional α/β discrimination applied to eliminate any contribution from α particles; (4) pairs of correlated events (with time interval $\Delta t{\leq}8.2$ ms between signals) are removed. In the inset, the simulated response function for external ^{40}K gammas is shown together with the experimental data.

On the next stage of the data selection we applied a cut on the reconstructed radius. In the energy region 1–2 MeV we used $R \leq 100$ cm cut aiming to remove the surface background events (mainly due to the ^{40}K decays outside the inner vessel) and leave the events uniformly distributed over the detector volume. The efficiency of the cut has been studied with MC simulation and lays in the range of $\epsilon_R = 0.76 - 0.80$ in the energy region 1–2 MeV. Additional α/β discrimination [25] was applied to eliminate contribution from α particles (spectrum 3 in fig. 1).

The time-correlated events (that occurred in the time window Δt<8.2 ms) were also removed (spectrum 4). The peak at 1.46 MeV, present in all spectra, is due to ^{40}K decays outside the scintillator, mainly in the ropes supporting the nylon sphere. The peak-like structure at ∼6.2 MeV is caused by saturation of the electronics by high-energy events. The lower spectrum of fig. 1 presents all the candidate scintillation events in the search for the decay of radioactive nuclides created in the active volume of the CTF after the nucleon disappearance in parent nuclei.

3 Data analysis and results

3.1 Theoretical considerations

The decay characteristics of the daughter nuclides, resulting from N and NN decays in parent nuclei – ^{12}C, ^{13}C and ^{16}O – contained in the sensitive volume of the CTF liquid scintillator or in the water shield, are listed in table 2.

Table 2
Initial nuclei in the Counting Test Facility, their abundance δ [32], processes with $\Delta B = 1, 2$ and characteristics of daughter nuclides [33].

Initial nucleus	Decay	Daughter nucleus, half-life, modes of decay and energy release		
$^{12}_{6}$C	n	$^{11}_{6}$C	$T_{1/2}$=20.38 m	β^+ (99.76%), EC(0.24%); Q=1.982 MeV
δ=98.93%	p	$^{11}_{5}$B	stable	
	nn	$^{10}_{6}$C	$T_{1/2}$=19.2 s	β^+; Q=3.651 MeV
	pn	$^{10}_{5}$B	stable	
	pp	$^{10}_{4}$Be	$T_{1/2}$=1.6·10^6 y	β^-; Q=0.556 MeV
$^{13}_{6}$C	n	$^{12}_{6}$C	stable	
δ=1.07%	p	$^{12}_{5}$B	$T_{1/2}$=20.4 ms	β^-; Q=13.370 MeV
	nn	$^{11}_{6}$C	$T_{1/2}$=20.38 m	β^+ (99.76%), EC(0.24%); Q=1.982 MeV
	pn	$^{11}_{5}$B	stable	
	pp	$^{11}_{4}$Be	$T_{1/2}$=13.8 s	β^-; Q=11.508 MeV
$^{16}_{8}$O	n	$^{15}_{8}$O	$T_{1/2}$=122 s	β^+ (99.89%), EC(0.11%); Q=2.754 MeV
δ=99.757%	p	$^{15}_{7}$N	stable	
	nn	$^{14}_{8}$O	$T_{1/2}$=70.60 s	β^+; Q=5.145 MeV
	pn	$^{14}_{7}$N	stable	
	pp	$^{14}_{6}$C	$T_{1/2}$=5730 y	β^-; Q=0.156 MeV

After the disappearance of one or two nucleons in the parent nuclide, one or

two holes appear in the nuclear shells; these holes will be filled in a subsequent nuclear de-excitation process, unless the nucleons reside on the outermost shells. If the initial excitation energy, E_{exc}, is higher than the binding energy S_N of the least bound nucleon (N is p or n), the nucleus will be de-excited by particle emission (p, n, α, d, etc.); otherwise ($E_{exc} < S_N$) a γ quantum will be emitted. In the following, we will take into consideration the N and NN decays from the last filled single-particle levels, when only γ quanta could be emitted. Thus the daughter nucleus is exactly known. We also neglect by the prompt signal from gamma quanta emitted in initial deexcitation process (in particular, because of generally big half lives of daughter nuclei, and uncertainty in the number of emitted γ's, their energies, and rejection of high energy events by the muon veto), and search only for subsequent radioactive decay of created nuclei.

The number of nucleons or nucleon pairs participating in the process can be calculated following refs. [13,15]. For example, after the decay of a neutron with binding energy $E_n^b(A,Z)$, the excitation energy of the $(A-1,Z)$ daughter nucleus will be $E_{exc} = E_n^b(A,Z) - S_n(A,Z)$. The condition to emit only γ quanta in the deexcitation process, $E_{exc} < S_N(A-1,Z)$, gives this restriction on the neutron binding energy: $E_n^b(A,Z) < S_n(A,Z) + S_N(A-1,Z)$. Similar equations can be written for p, pp, pn and nn decays (see ref. [15]). The values of the separation energies S_N and S_{NN} were taken from ref. [34]. For single-particle energies of nucleons $E_{p,n}^b$ on nuclear shells we used the continuum shell model calculations [35] for ^{12}C and ^{13}C, and the Hartree-Fock calculations with the Skyrme's interaction [36] for ^{16}O.

3.2 Simulation of the response functions

The expected response functions of the CTF detector and related efficiencies for the decay of unstable daughter nuclei were simulated with the EGS4 package [37]. The number of initial electrons and γ quanta emitted in the decay of the nucleus and their energies were generated according to the decay schemes [33]. The events were supposed to be uniformly distributed in the whole volume of the liquid scintillator (and in a water layer close to the LS). The energy and spatial resolution of the detector [29], light quenching factors for electrons and gammas [28], μ veto and triggering efficiency were taken into account in the simulations. The calculated responses for the decay of ^{11}C and ^{10}C in the liquid scintillator (created after n and nn disappearance in ^{12}C, respectively) and ^{14}O in the water shield (nn decay in ^{16}O) are shown in fig. 2. In the last case only the water layer of 1 m thickness closest to the liquid scintillator was taken into consideration. Contributions from layers further out are negligible.

The CTF background was simulated as well in order to check the understand-

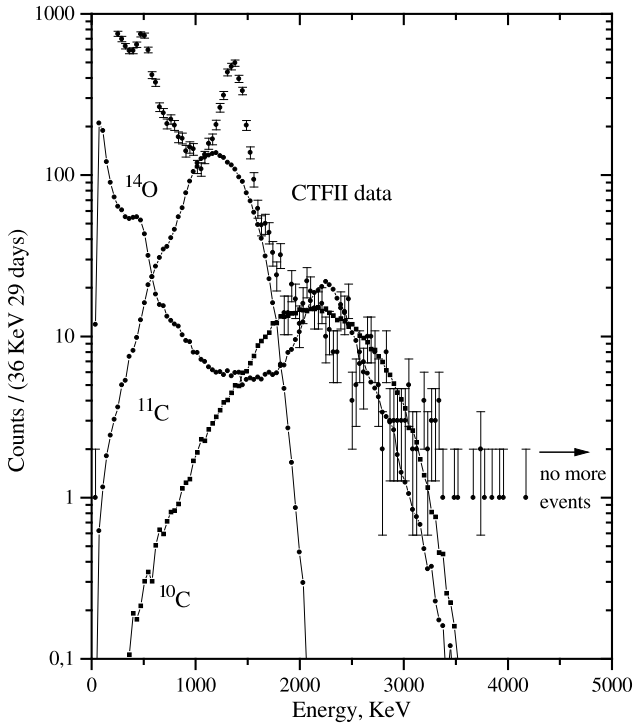


Fig. 2. Energy distribution of the CTF-II installation collected during 29.1 d with all cuts. The expected response functions of the detector are also shown for ^{11}C ($3.4{\cdot}10^3$ decays in the liquid scintillator; corresponding mean lifetime for the n decay is $\tau_n = 1.8{\cdot}10^{25}$ y), ^{10}C ($6.8{\cdot}10^2$ decays; $\tau_{nn} = 4.4{\cdot}10^{25}$ y), and ^{14}O ($1.4{\cdot}10^4$ decays in 1 m thick water layer closest to the sphere with liquid scintillator; $\tau_{nn} = 5.7{\cdot}10^{24}$ y).

ing of the detector. The simulated ^{40}K 1.46 MeV gamma peak together with experimental data is shown in the inset of fig. 1. The shift in the position of the full absorption peak is due to the ionization quenching effect (see section 2.2). One can see the good agreement between the experimental and simulated ^{40}K peak position and resolution.

3.3 Limits on probabilities of the N and NN disappearance

The experimental data (see fig. 2, where the spectrum with all cuts is shown in detail) gives no strong evidence of the expected N and NN decay response functions, thus allowing only bounds to be set on the processes being searched for. In the present study, in order to extract the limits on the relevant mean lifetimes, we assumed conservatively that *all* events in the CTF experimental spectrum in the corresponding energy range ΔE are due to nucleon decays.

The mean lifetime limit was estimated using the formula

$$\tau_{\rm lim} = \varepsilon_{\Delta E} \cdot N_{nucl} \cdot N_{obj} \cdot t / S_{\rm lim} = N_{nucl} \cdot N_{obj} \cdot t / D_{\rm lim}, \qquad (1)$$

where $\varepsilon_{\Delta E}$ is the detection efficiency in the ΔE energy window calculated in the full simulation of the relevant process, taking into account the radial cut efficiency ϵ_R, and probability of identification by muon veto η; N_{nucl} the number of parent nuclei; N_{obj} the number of objects (n, p or NN pairs) inside the parent nucleus whose decay will give the specific daughter nucleus; t the time of measurements; $S_{\rm lim}$ the number of events (in the ΔE window) due to a particular effect which can be excluded with a given confidence level on the basis of experimental data; and $D_{\rm lim} = S_{\rm lim}/\varepsilon_{\Delta E}$ the corresponding number of decays in the liquid scintillator/water.

The parameters in (1) were defined in the following way. The mass of scintillator was defined measuring the buoyancy with a precision of 5%. The total time of the data taking is 29.1 days and takes into account the dead time of the electronics of $\simeq 3\%$. The measurements were performed in runs of about 24 hours. The internal source of ^{40}K was used to check the energy calibration stability. The position of the ^{40}K peak was defined for every run with statistical accuracy of $\simeq 20$ keV. No systematical shift in energy scale with a time has been found. The same is valid for the energy resolution, which is directly connected to the energy scale. In addition, all the response functions for the searched decays are wider than detector's resolution, hence the result is insensitive to the observed energy scale uncertainties.

The probability of detecting scintillation events by the muon veto $\eta = 1 \pm 0.2\%$ has been defined from the experimental data for the energy $E = 1.9$ MeV. This value is in agreement with the MC simulation. For $\eta(1.9\ \text{MeV}) = 1.2\%$ the changes in the integral efficiency $1 - \eta(E)$ is negligible in the case of n and nn decays, for the p and pp decays the $\varepsilon_{\Delta E}$ will decrease by 7%.

3.3.1 n and nn disappearance

For the nn decay, there are four neutrons on the outermost $1p_{3/2}$ level of ^{12}C which gives the number of nn pairs $N_{obj} = 2$. The disappearance of the nn pair from this level will result in a ^{10}C nucleus in the ground state. Taking into account the statistical uncertainty in the number of experimental events in the 2.0–3.0 MeV energy window (276±17), we calculate $S_{\rm lim} = 297$ at 90% C.L. Accounting for the associated efficiency $\varepsilon_{\Delta E} = 0.44$, the limiting value for ^{10}C decays is $D_{\rm lim} = 6.8 \cdot 10^2$. With the values of $N_{nucl} = 1.9 \cdot 10^{29}$ for ^{12}C nuclei and $t = 29.1$ d, we obtain

$$\tau_{\rm lim}(nn, ^{12}\text{C}) = 4.4 \cdot 10^{25}\ \text{y with 90\% C.L.}$$

For the ^{16}O nucleus we will account for only one nn pair on the outermost $1p_{1/2}$ orbit (nn decay in deeper levels will result the ^{16}O nucleus being too excited). With the number of ^{16}O nuclei (in a 1 m thick water layer) $N_{nucl} = 9.8 \cdot 10^{29}$, $N_{obj} = 1$ and $D_{\rm lim} = 1.4 \cdot 10^4$ for the energy region 2.2–2.6 MeV, the result is

$$\tau_{\rm lim}(nn,^{16}{\rm O}) = 5.7 \cdot 10^{24} \text{ y with } 90\% \text{ C.L.}$$

With the assumption that the mean lifetime of the nn pair is the same in ^{12}C and ^{16}O nuclei, and that nn decays in both of them contribute to the experimental spectrum simultaneously, one can obtain a slightly more stringent limit for nn decay:

$$\tau_{\rm lim}(nn \to inv) = 4.9 \cdot 10^{25} \text{ y with } 90\% \text{ C.L.}$$

For n decay in ^{12}C we used a similar approach, just demanding that the simulated response function for ^{11}C decay should be equal to the experimental spectrum in the energy region of 1.0–1.1 MeV (fig. 2). In this way the value $D_{lim} = 3.4 \cdot 10^3$ was determined for the full number of ^{11}C decay events. Together with $N_{obj} = 4$ (four neutrons on the $1p_{3/2}$ level), it gives the following limit:

$$\tau_{\rm lim}(n,^{12}{\rm C}) = 1.8 \cdot 10^{25} \text{ y with } 90\% \text{ C.L.}$$

3.3.2 p and pp disappearance

As for the p and pp decays into invisible channels, the p disappearance in ^{13}C will result in ^{12}B nuclei, the β^- decaying with high energy release Q=13.370 MeV. The pp decays in ^{13}C will produce ^{11}Be nuclei, also the β^- decaying with Q=11.508 MeV (with probability of decay to the ground state of 57%).

To estimate the $\tau_{\rm lim}$ for p and pp instabilities, we use the fact that no candidate scintillation events were observed in the CTF spectrum with energies higher than 4.5 MeV (fig. 2).

High energy release in the liquid scintillator can activate the muon veto of the CTF, resulting in rejection of the event. We take into account such a suppression of high energy tails in β decays of ^{12}B and ^{11}Be using the probability $\eta(E)$ for identification of an event with energy E in the LS by the muon veto (fig. 3). The beta spectra of ^{12}B and ^{11}Be without and with suppression by the muon veto are also shown in fig. 3. The part of the ^{12}B beta spectrum with $E \geq 4.5$ MeV reduced by a factor of $1-\eta(E)$ gives an integrated efficiency $\varepsilon_{\Delta E} = 0.39$. With zero observed events (and with the assumption of zero expected background), the limiting value for the number of events is $S_{\rm lim} = 2.44$ with 90% C.L. in accordance with the Feldman-Cousins procedure [38] recommended by the Particle Data Group [9]. Thus we arrive at the value $D_{\rm lim} = 6.2$ for ^{12}B

decay. Together with $N_{nucl} = 2.1 \cdot 10^{27}$ for parent ^{13}C nuclei and the number of $N_{obj} = 4$ for protons in $1p_{3/2}$ orbit, we obtain

$$\tau_{\rm lim}(p,^{13}{\rm C}) = 1.1 \cdot 10^{26} \text{ y with 90\% C.L.}$$

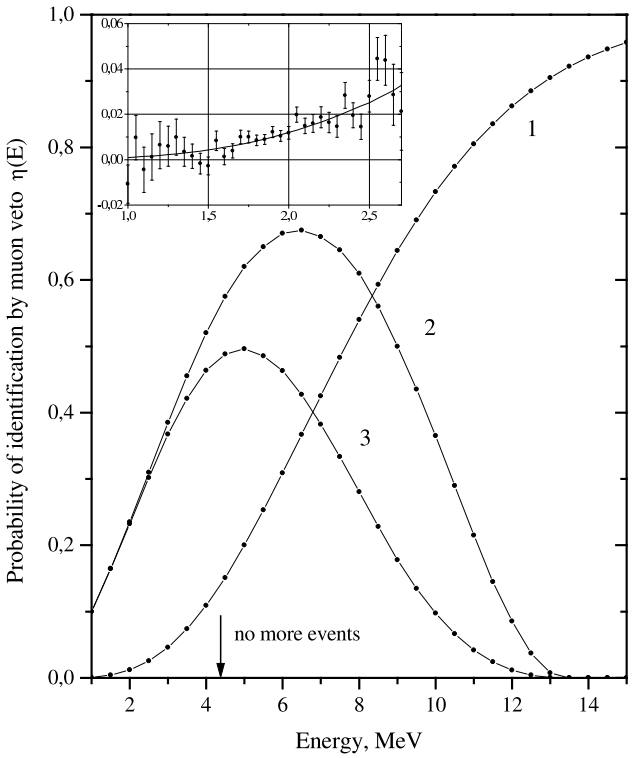


Fig. 3. Probability of identification of an event with energy E in the scintillator by the muon veto (1). The β spectra of ^{12}B without (2) and with (3) suppression by the muon veto are also shown in arbitrary units. For signals with $E < \simeq 3$ MeV (^{10}C, ^{11}C and ^{14}O decays), μ veto does not have a big effect on the overall efficiency. In the inset the experimental data taken with the radon source are presented. The tagged events of ^{214}Bi–^{214}Po at the energy E=1.9 MeV are 'seen' by the muon veto system with an efficiency of $\eta = 0.01$.

In a similar way, for the pp decay in ^{13}C with the value $N_{obj} = 2$ for the number of pp pairs and $\varepsilon_{\Delta E} = 0.36$, the mean lifetime limit is

$$\tau_{\rm lim}(pp,^{13}{\rm C}) = 5.0 \cdot 10^{25} \text{ y with 90\% C.L.}$$

All mean lifetime limits obtained here together with the numbers of parent nuclei, N_{obj} and the numbers of decay events are summarized in table 3.

Table 3
Mean lifetime limits, $\tau_{\rm lim}$, (at 90% C.L.) for N and NN decays in the CTF. N_{nucl} is the number of parent nuclei; N_{obj} the number of objects (n, p and NN pairs) per parent nucleus; $D_{\rm lim}$ the excluded number of decay events.

	Decay	N_{nucl}	N_{obj}	$D_{\rm lim}$	$\tau_{\rm lim}$, y
p	$^{13}_{6}\mathrm{C}\rightarrow^{12}_{5}\mathrm{B}$	$2.1{\cdot}10^{27}$	4	6.2	$1.1 \cdot 10^{26}$
n	$^{12}_{6}\mathrm{C}\rightarrow^{11}_{6}\mathrm{C}$	$1.9{\cdot}10^{29}$	4	$3.4 \cdot 10^{3}$	$1.8 \cdot 10^{25}$
nn	$^{12}_{6}\mathrm{C}\rightarrow^{10}_{6}\mathrm{C}$	$1.9{\cdot}10^{29}$	2	$6.8 \cdot 10^{2}$	$4.4 \cdot 10^{25}$
	$^{16}_{8}\mathrm{O}\rightarrow^{14}_{8}\mathrm{O}$	$9.8{\cdot}10^{29}$ [a]	1	$1.4 \cdot 10^{4}$	$5.7 \cdot 10^{24}$
pp	$^{13}_{6}\mathrm{C}\rightarrow^{11}_{4}\mathrm{Be}$	$2.1{\cdot}10^{27}$	2	6.7	$5.0 \cdot 10^{25}$

[a] In 1 m thick layer of water closest to the CTF liquid scintillator

4 Conclusions

Using the unique features of the BOREXINO Counting Test Facility – the extremely low background, the large scintillator mass of 4.2 ton and the low energy threshold – new limits on N and NN decays into invisible channels (disappearance, decays to neutrinos, majorons, etc.) have been set:

$\tau(n \rightarrow inv) > 1.8 \cdot 10^{25}$ y, $\tau(p \rightarrow inv) > 1.1 \cdot 10^{26}$ y,

$\tau(nn \rightarrow inv) > 4.9 \cdot 10^{25}$ y and $\tau(pp \rightarrow inv) > 5.0 \cdot 10^{25}$ y with 90% C.L.

Comparing these values with the data of table 1, one can see that the established limits for nn and pp decays are the best up-to-date limits set by any method, including radiochemical and geochemical experiments.

These limits are obtained in a very conservative assumption that all events in the corrresponding energy region are due to the nucleon decays. The data from the full scale Borexino detector will improve the presented limits by at least two orders of magnitude.

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